an experimental program for extra dimensions

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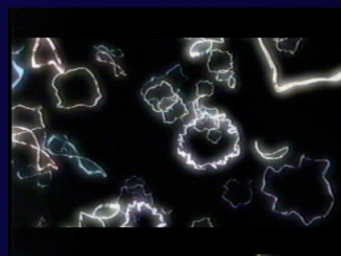
extra dimensions: fun or physics?

"A thousand flies can't be wrong" - S.D.

- despite ~3000 recent papers on ED, and 100 different models, are we really serious?
- the (4d) SUSY desert remains the dominant paradigm for BSM physics
- is ED just a jobs program for theorists?

hyperspace is no joke

the big picture
(see e.g. CERN colloquium by David Gross)

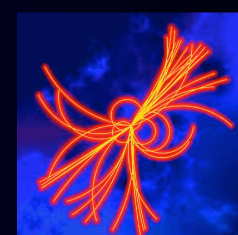


string unification

supersymmetry *extra dimensions*

broken hidden

new TeV scale physics



+ *neutrinos, cosmology, rare processes, astrophysics, etc*

the two big ideas

- note SUSY and extra dimensions are not mutually exclusive!
- strings require both
- ED probably needs SUSY to be stable
- SUSY probably needs ED to be pretty

why extra dimensions?

- the Standard Model
- string theory
- general relativity

the Standard Model
flavor structure is too complicated
for a theory of “elementary” constituents

what is this telling us?

- for molecules, atoms, and hadrons, the answer is that they are composites
- but e.g. the electron is pointlike on scales <1/100,000 x its Compton wavelength
- except for the top quark, compositeness looks like a bad bet

the Standard Model flavor structure is too complicated for a theory of "elementary" constituents

- another answer is that there are broken flavor symmetries, probably gauged, combined somehow with GUT
- requires lots of new degrees of freedom and new dynamics to get back to SM
- difficult, messy, *ad hoc*
- ditto for extended technicolor schemes

the Standard Model flavor structure is too complicated for a theory of "elementary" constituents

- ED's (potentially) explain flavor structure via geometry
- hard to believe that ED's aren't at least *part* of the answer
- note since we don't know the scales that generate the SM flavor structure, this insight doesn't tell us the scale of the EDs!

string theory

- it is not surprising that when you quantize a relativistic extended object it turns out to have a critical dimension
- for superstrings the critical dimension is 10, not 4, and this is very fortunate...

string theory

- since strings have Planck scale built in, the SM has to come from the *zero modes*
- without ED's the zero mode spectrum of strings would be too simple
- if strings were 4d they would be ruled out already!

general relativity

- the fact that your GPS works shows that spacetime is dynamical
- string theory shows that consistent nonsingular dynamics can change both the dimensionality and topology of space
- so the number of spatial dimensions is not fundamental - it is a dynamical quantity which may vary with time, energy scale, or the physical system being probed

what is the energy scale of ED's?

- we don't know
- but as with SUSY we expect ED's to appear at scales associated with other kinds of physics
- there are three or four plausible candidate scales:

what is the energy scale of ED's?

- the GUT/Planck/see-saw scale, i.e. the superheavy region around $10^{15} - 10^{18}$ GeV
- the TeV scale, i.e. 100 GeV - 10 TeV
- the dark energy/neutrino mass scale, i.e. $\frac{\mathrm{TeV}^2}{M_{\mathrm{planck}}}$

the GUT scale seems the most likely!
but some of the ED's could show up sooner

the trouble with
extra dimensions models:

(1) there are too many of them

the trouble with
extra dimensions models:

(1) there are too many of them

(2) none of them are any good

partial bestiary of ED models

- ADD: 2-6 large circular ED's, SM on a brane, gravity in bulk
- RS-1: one small warped ED with brane at each end, SM on TeV brane
- RS-1 variations: as above but redistribute SM and other particles between TeV brane, Planck brane, and bulk, or add second warped ED
- RS-2 and LR: one infinite warped ED, light KK gravitons
- DGP: one or more infinite (or large) flat (or slightly warped) ED's
- UED: one or more TeV^{-1} sized ED's, SM in the bulk, branes are for symmetry-breaking
- generic braneworlds: SM on various branes, 6-7 small ED's, complicated (but stable?) symmetry-breaking geometries
- deconstructed ED's: new degrees of freedom approximately resemble an ED in some energy regime

none of them are any good

- most are scenarios rather than models
- scenario = set of physical assumptions which, with more work, could turn into a respectable class of models
- many have deep theoretical problems or “gaps”
- many have generic phenomenological problems
- no benchmarks!

but models suggest that ED's can do a lot:

- explain (or assist) EWSB
- explain dark matter
- lower the effective Planck or string scale
- break SUSY
- explain (some) flavor properties of SM
- improve grand unification
- explain neutrino physics
- explain dark energy

what is the physics that hides extra dimensions?

possible explanations:

- the extra dimensions are compact and small (circle, torus, line interval, sphere, Calabi-Yau, etc)
- Some/all SM particles are trapped on a brane and only probe the dimensions of that brane, not the full extra dimensional “bulk” space
- the extra dimensions are fundamentally different (fermionic=SUSY, discretized, ...)
- some combination of the above

three classes of LHC-friendly models

- UED
- ADD
- RS

UED = Universal Extra Dimensions

Appelquist, Cheng, Dobrescu

- basically the same as Kaluza and Klein
- all particles probe all dimensions (i.e. live in the bulk)
- extra dimensions are "orbifolds" of circles with common radius R
- so we should see Kaluza-Klein modes with mass ~1/R, could be as low as ~300 GeV

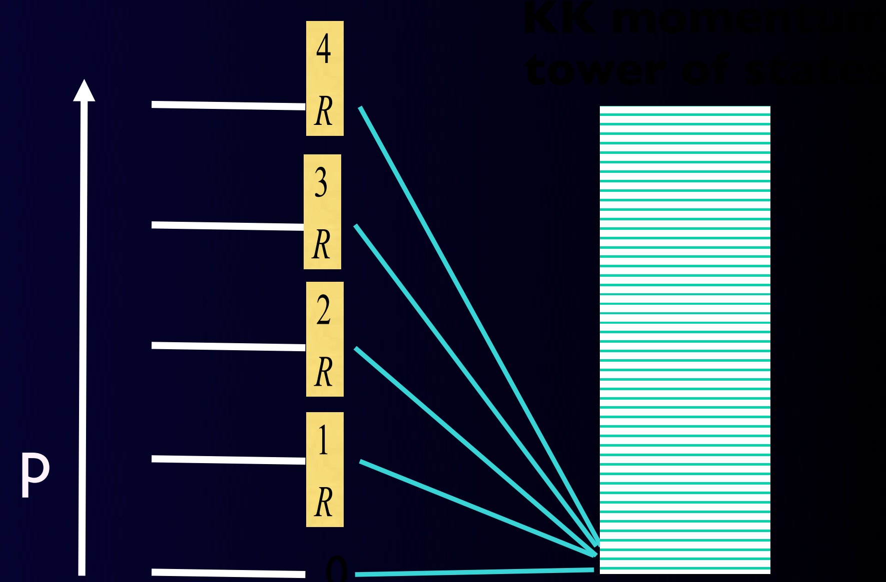
Kaluza-Klein modes

if spatial dimension is compact
then momentum in that
dimension is quantized:

$$p = \frac{n}{R}$$

from our point of view we see new massive particles

$$m^2 = m_0^2 + \frac{n^2}{R^2}$$



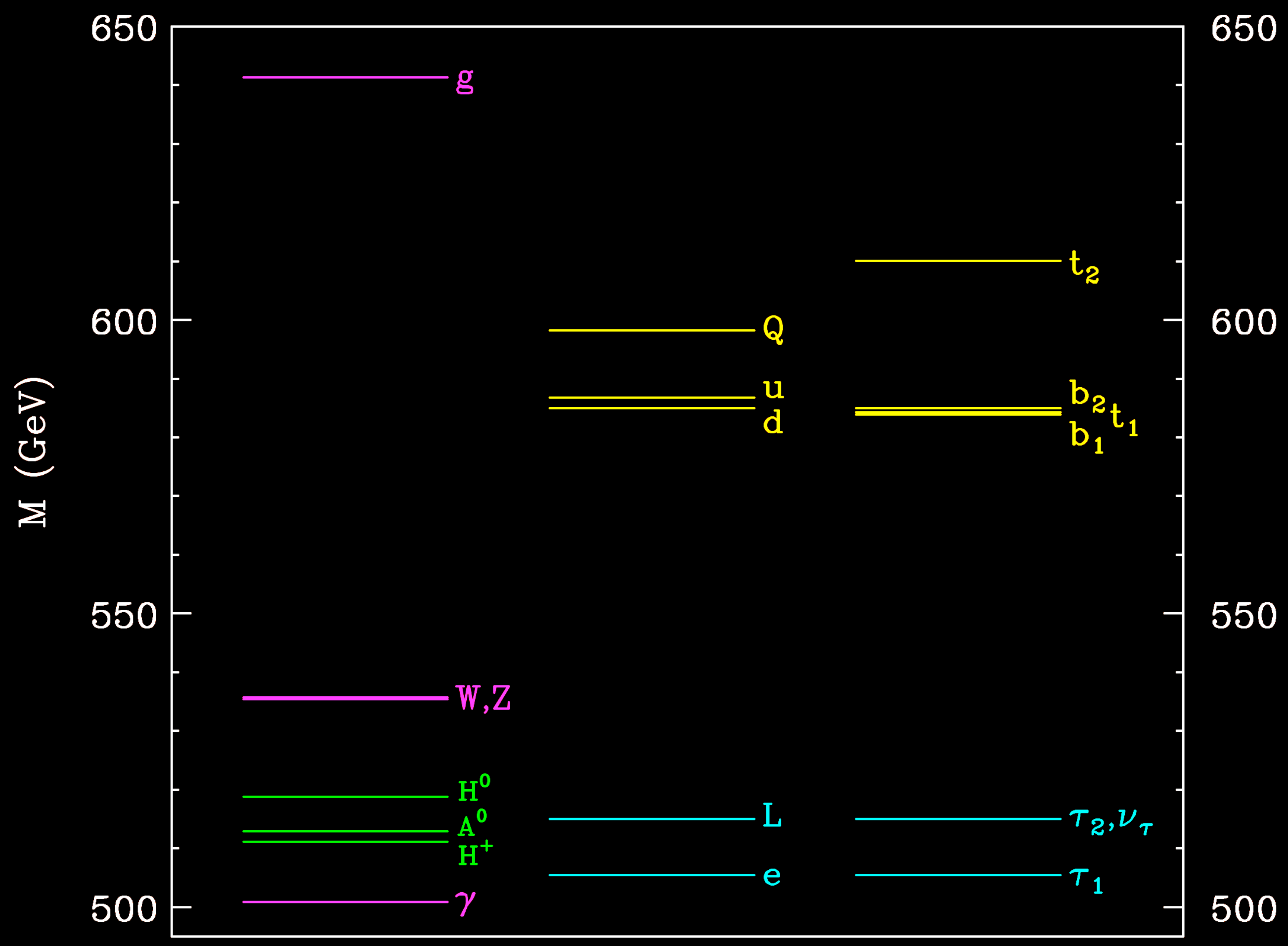
UED = Universal Extra Dimensions

- the "orbifold" means we truncate the circles to line intervals, and keep only even or odd KK modes for each kind of particle
- e.g. for a 5dim gauge boson $\mathbf{A_M = (A_\mu, A_5)}$, keep only the even KK modes of $\mathbf{A_\mu}$, and only the odd KK modes of $\mathbf{A_5}$ (since it appears in a covariant derviative with $\mathbf{d/dx^5}$).
- thus the orbifolding avoids having massless scalars in the adjoint of the SM gauge group!
- orbifolding also allows chiral fermion zero modes

UED = Universal Extra Dimensions

- the orbifolding breaks translational symmetry around the circles, so KK momentum is no longer conserved
- but a discrete remnant of KK momentum conservation, called KK parity, is conserved
- this is like R parity in SUSY
- it means that KK modes in UED have to be pair-produced
- and the lightest massive KK mode (the LKP) is stable (a dark matter candidate too)

lowest KK modes of UED look like SUSY!



Cheng, Matchev, Schmaltz, hep-ph/0205314

force laws in extra dimensions

$$\vec{\mathbf{F}} = \mathbf{q}\vec{\mathbf{E}} = \frac{\mathbf{qQ}}{4\pi\mathbf{r^2}}\hat{\mathbf{r}}$$

usual 4d Coulomb's law is derived from Gauss' law

$$\oint \vec{\mathbf{E}} \cdot \vec{\mathbf{d}}\mathbf{A} = \mathbf{Q}$$

$$\vec{\mathbf{F}} = -\mathbf{G_N}\frac{\mathbf{mM}}{\mathbf{r^2}}\hat{\mathbf{r}}$$

true also for Newton's gravitational force law

$$\oint \frac{\vec{\mathbf{F}}}{\mathbf{m}} \cdot \vec{\mathbf{d}}\mathbf{A} = \frac{4\pi\mathbf{M}}{\mathbf{M^2_{\mathrm{Planck}}}}$$

$$\mathbf{G_N} = \frac{1}{\mathbf{M^2_{\mathrm{Planck}}}}$$

$$\mathbf{M_{\mathrm{Planck}}} = \mathbf{1.22} \times \mathbf{10^{19}\ GeV}$$

force laws in extra dimensions

in 4+n dimensions (i.e. 3+n spatial dimensions), can still use Gauss' law to figure out the force law

$$\vec{\mathbf{F}} = -\frac{\mathbf{mM}}{\mathbf{M_*^{2+n} r^{2+n}}}\hat{\mathbf{r}}$$

analog of $\mathrm{M_{Planck}}$

if the n extra dimensions are compact, with volume $\mathbf{V}$, then at larger distances the $\frac{1}{\mathbf{r^{2+n}}}$ force law must go back to the usual $\frac{1}{\mathbf{r^2}}$

and we can match the gravitational constants:

$$\mathrm{M}^{\mathbf{2}}_{\mathrm{Planck}} = \mathrm{M}_*^{\mathbf{2+n}}\,\mathbf{V}$$

ADD braneworld models

Arkani-Hamed, Dimopoulos, Dvali

assume that only gravity sees n large extra compact dimensions with common circumference R:

$$\mathbf{M^2_{\mathrm{Planck}} = M_*^{2+n}\, R^n}$$

in ADD models M_* is supposed to be of order a TeV. Then the largeness of R generates the observed hierarchy between the Planck scale and the electroweak scale

these are large extra dimensions

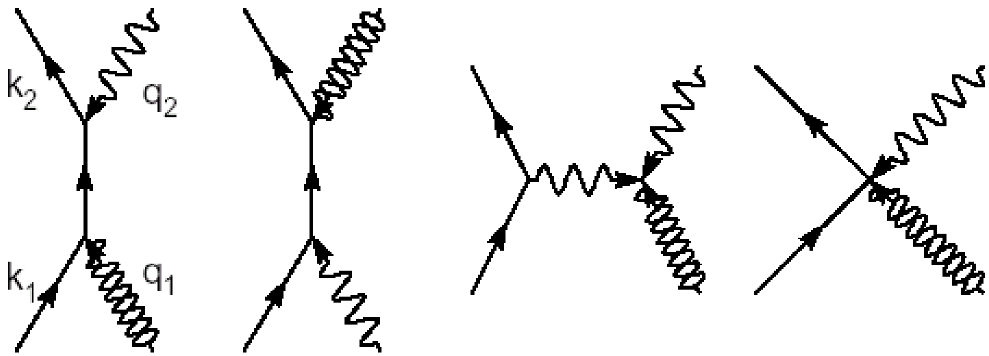
$n = 1$	$\Longrightarrow$	$R \sim 10^9\,\mathrm{Km}$	**Solar system**
$n = 2$	$\Longrightarrow$	$R \sim 1\mathrm{mm}$	**Pinhead**
$n = 3$	$\Longrightarrow$	$R \sim 1\mathrm{nm}$	**Gold atom**
$n = 6,7$	$\Longrightarrow$	$R \sim 10\ \mathrm{fm}$	

we can test these models in a variety of experiments

quantum gravity at colliders

if ADD is correct collider expts should see effects of both real and virtual massive KK gravitons

$$\sigma_{\mathbf{KK}} \sim \frac{\mathbf{1}}{\mathbf{M}^{\mathbf{2}}_{\mathrm{Planck}}}(\mathbf{ER})^{\mathbf{n}} \sim \frac{\mathbf{1}}{\mathbf{M}^{\mathbf{2}}_{*}}\left(\frac{\mathbf{E}}{\mathbf{M}_{*}}\right)^{\mathbf{n}}$$



KK graviton production (monojets)

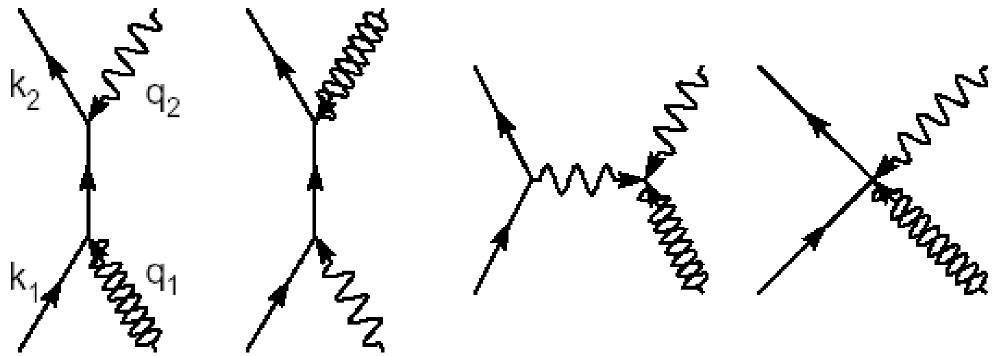
(HLZ): Han, JL, and Zhang, hep-ph/9811350
(GRW): Giudice, Rattazzi, Wells, hep-ph/9811291

$$\sigma(1+2 \to \mathbf{KK}+4) = \int \mathbf{dx_1 dx_2 d\hat{t}\, f_1(x_1) f_2(x_2)} \int_0^{\sqrt{\hat{s}}} \mathbf{dm}\, \rho(\mathbf{m}) \frac{\mathbf{d}\sigma_{\mathbf{m}}}{\mathbf{d\hat{t}}}(\hat{\mathbf{s}}, \hat{\mathbf{t}})$$

the dependence on "n", the number of extra dimensions, is all in the KK density of states:

$$\rho(\mathbf{m}) = \frac{\mathbf{M}^2_{\mathrm{Planck}}}{\mathbf{M}^3_{\mathbf{s}}} \left(\frac{\mathbf{m}}{\mathbf{M_s}}\right)^{\mathbf{n-1}}$$

$$\mathbf{M}_{\mathbf{s}}^{\mathbf{n+2}} = \frac{(\mathbf{2}\pi)^{\mathbf{n}}}{\mathbf{S_{n-1}}} \mathbf{M}_*^{\mathbf{n+2}} = \mathbf{2}^{\mathbf{n-1}} \pi^{\mathbf{n/2}} \Gamma(\frac{\mathbf{n}}{\mathbf{2}}) \mathbf{M}_*^{\mathbf{n+2}}$$



KK graviton production (monojets)

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$$\sigma(\mathbf{q\bar{q}} \to \mathbf{KK} + \mathbf{g})$$

$$= \frac{\mathbf{2\pi\alpha_s}}{\mathbf{9M^2_{\rm Planck}}} \int \mathbf{dx_1 dx_2 dm d\hat{t}\, f_1(x_1) f_2(x_2)\, \rho_n(m)\, \frac{1}{\hat{s}} F_1(\frac{\hat{t}}{\hat{s}}, \frac{m^2}{\hat{s}})}$$

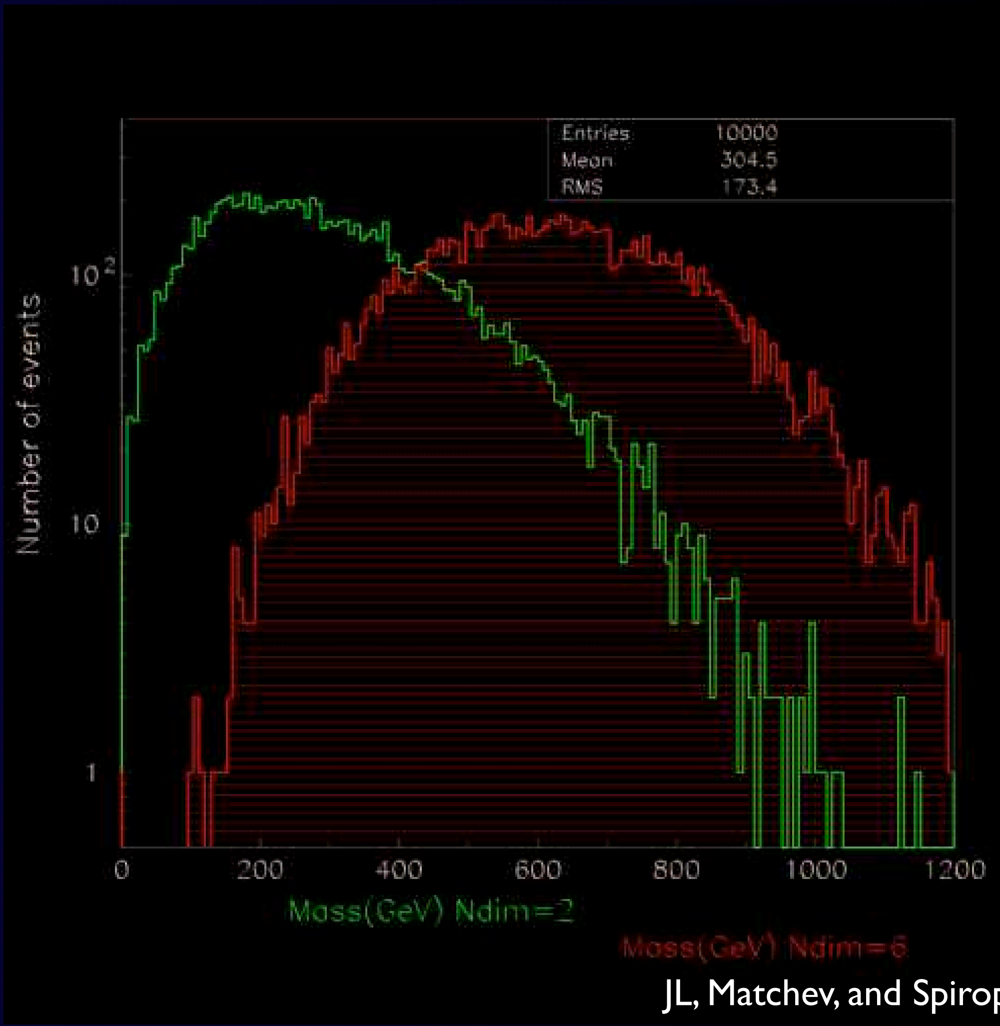
$$F_1(x,y) = \frac{1}{x(y-1-x)}\Big[-4x(1+x)(1+2x+2x^2)+ \\ y(1+6x+18x^2+16x^3) - 6y^2x(1+2x) + y^3(1+4x)\Big],$$

this is the KK graviton spectrum, as it would be produced at the Tevatron for $M_s \sim 1$ TeV

the n=6 KK gravitons are about 3 times heavier than for n=2

this is because the cross section formula, integrated over x_1, x_2, and $\hat{t}$, gives

$$\sigma \sim \int_0^{\sqrt{s}} dm \left(1 - \frac{m}{\sqrt{s}}\right)^{2p} \left(\frac{m}{\sqrt{s}}\right)^n$$



JL, Matchev, and Spiropulu

with $p \sim 6$ from the pdfs $\longrightarrow$ peaks at $\frac{m}{\sqrt{s}} \sim \frac{n}{2p}$

But, the pT distribution of the recoiling jet is almost completely independent of the number of extra dims!

this is because

$$\mathrm{m^n = (\sqrt{\hat{s}})^n \left(\frac{m}{\sqrt{\hat{s}}}\right)^n = (\sqrt{\hat{s}})^n y^{n/2}}$$

for a given fixed $\hat{\mathrm{s}}$, this wants $\mathrm{y} \sim 1$, i.e. production near threshold.

This effect suppresses pT for fixed $\hat{\mathrm{s}} \simeq \mathrm{m}$, by $1/\mathrm{n}$

so to count the number of dims you probably have to vary s.

RS = Randall Sundrum

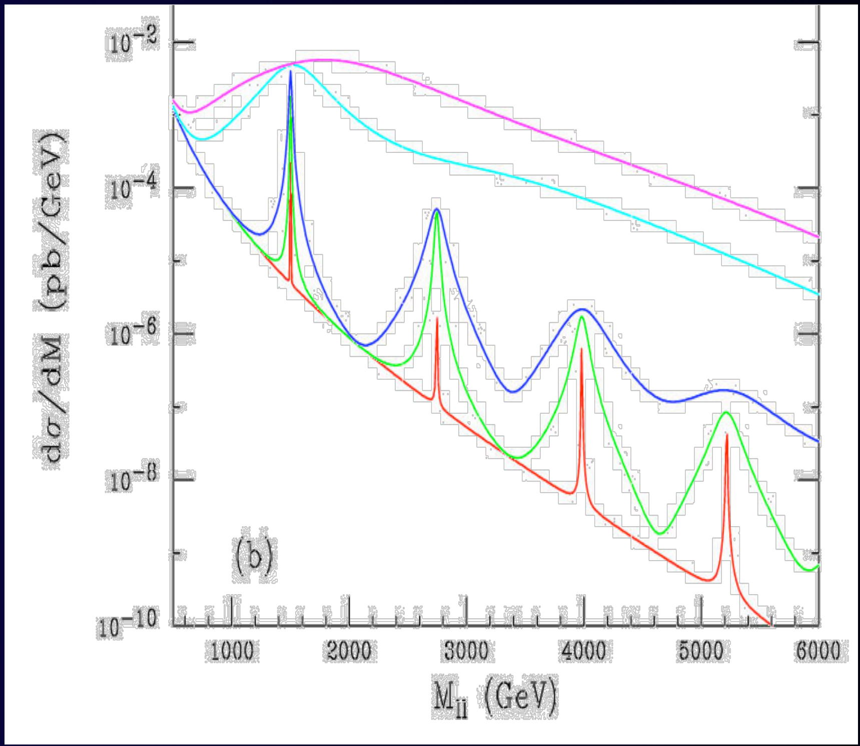
Randall and Sundrum (!)

- only one extra dimension, and at least one brane
- but the extra dimension has negative curvature ("warped", "AdS") caused by the brane
- there are many versions of RS, but when phenomenologists say RS they always mean RS-1
- RS-1 means the fifth dim is a line interval; at one end is the "Planck brane", at the other end is the "TeV" brane
- all/some SM particles live on the TeV brane

RS = Randall Sundrum

- the KK gravitons have masses ~ TeV, and their couplings to SM particles are only TeV suppressed, not Planck suppressed
- so at the LHC you can see them as difermion resonances

Davoudiasl, Hewett, Rizzo



what defines an ED scenario?

- number of ED’s at each scale
- what is the compactification?

  - what is the geometry?
  - are there background fields, e.g. gauge fluxes, in the EDs?
  - what symmetries are broken/unbroken?
  - is there curvature/warping in the bulk?
  - are there visible radions or other moduli fields?

what defines an ED scenario?

- what is gravity doing?
- who is on the branes and who is in the bulk?

  - who has KK modes?
  - who gets volume-suppressed couplings?

- what about stability? consistency? UV completion?

experimental issues = opportunities

- how do you know it is ED and not something else?
- how to get experimental handles on all the features of ED scenarios
- direct versus indirect versus really indirect
- event generation and benchmark models
- collider vs flavor vs astro signals/constraints

who’s on the bench?

- SUSY has official benchmark models ratified by intergalactic treaties
- ED has no benchmark models at all
- some of the most popular ED models, e.g. n=2 ADD, are not suitable benchmarks as they are already experimentally excluded
- this needs to change before 2007

event generators for ED

- until recently, the only event generators for ED models were custom hacks:
- ADD in Pythia (Matchev + JL bootleg) used for CDF and D0 monjet analyses
- ADD in Isajet (Hinchliffe + Vacavant) used for ATLAS monojet studies, now in official Isajet release
- RS-I in Herwig, also used for Atlas studies
- nothing in CompHEP

event generators for ED

- very recently, AMEGIC has implemented complete ADD Feynman rules (Gleisberg, Krauss, Matchev)
- seems like a big step forward
- if you are very nice to Frank Krauss, he will probably let you use it

lots to do

- I have left out a lot; this is just a sample
- let's create a serious experimental program for extra dimensions at the LHC!